

Strangeness and Hadron Structure

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The nucleon wave function may contain a significant component of $\bar{s}s$ pairs, according to several measurements including the π -nucleon σ term, charm production and polarization effects in deep-inelastic scattering. In addition, there are excesses of ϕ production in LEAR and other experiments, above predictions based the naive Okubo-Zweig-Iizuka rule, that may be explained if the nucleon wave function contains a polarized $\bar{s}s$ component. This model also reproduces qualitatively data on Λ polarization in deep-inelastic neutrino scattering. The strange component of the proton is potentially important for other physics, such as the search for astrophysical dark matter.

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1. Strange Ideas

Does the nucleon wave function contain a (large) strange component? The starting point for any discussion of the quark flavour content is the amazingly successful naïve quark model (NQM), in which $|p\rangle = |UUD\rangle$, with each constituent quark weighing $m_{U,D} \sim 300$ MeV [1]. A simple non-relativistic S -wave function with $v/c \ll 1$ is surprisingly successful: even better is a simple harmonic oscillator potential with a D -wave admixture of 6% (in amplitude) [2]. For comparison, we recall that the deuteron and ${}^3\text{He}$ wave functions contain similar D -wave admixtures. Neglecting any such D -wave component, the (overly?) naïve quark model would predict that the proton spin is the algebraic sum of the constituent quark spins: $\underline{s}_P = \underline{s}_U + \underline{s}_U + \underline{s}_D$. Axial current matrix elements indicated that the quark spins might contribute at most 60% of the proton spin, even before the EMC and its successor experiments [3], but we return to this later. Whatever the partial-wave decomposition, if the proton only contains $|UUD\rangle$ Fock states, and one neglects pair creation, a consequence is the Okubo-Zweig-Iizuka (OZI) rule [4] forbidding the coupling of the proton $|\bar{s}s\rangle$ mesons. The validity of the OZI rule is another major theme of this talk.

Although the NQM is very successful, it has never been derived from QCD, and is expected to be wrong and/or incomplete [1]. The validity of chiral symmetry informs us that the light quarks are indeed very light: $m_{u,d} < 10$ MeV, $m_s \sim 100$ MeV [5]. These estimates refer to the current quarks visible in short-distance or light-cone physics. Such current quarks should be relativistic: $v/c \sim 1$, and there is no obvious reason why pair production of $\bar{u}u$, $\bar{d}d$ or $\bar{s}s$ should be suppressed. Indeed, non-perturbative interactions

with the flavour content $(\bar{u}u)(\bar{d}d)(\bar{s}s)$ are believed to be important [6] and the light quarks are known to condense in the vacuum [5]:

$$\langle 0|\bar{u}u|0\rangle \simeq \langle 0|\bar{d}d|0\rangle \equiv \langle 0|\bar{q}q|0\rangle \sim \langle 0|\bar{s}s|0\rangle \sim \Lambda_{QCD}^3, \quad (1)$$

where

$$m_\pi^2 \simeq \frac{m_u + m_d}{f_\pi^2} \langle 0|\bar{q}q|0\rangle, \quad m_K^2 \simeq \frac{m_s}{f_K^2} \langle 0|\bar{s}s|0\rangle. \quad (2)$$

Inside a proton or other hadron, one would expect the introduction of colour charges to perturb the ambient vacuum. Since the connected matrix element

$$\langle p|\bar{q}q|p\rangle \equiv \langle \bar{q}q \rangle_{\text{full}} - \langle 0|\bar{q}q|0\rangle \langle p|p\rangle, \quad (3)$$

one could expect that $\langle p|\bar{s}s|p\rangle \neq 0$.

There are many suggestions for improving the NQM, such as bag models [7] – in which relativistic quarks are confined within a cavity in the vacuum, chiral solitons [8] – which treat nucleons as coherent mesonic waves, and hybrid models [9] – which place quarks in cavities inside mesonic solitons. As an example of the opposite extreme from the NQM, consider the Skyrme model.

In this model [8], the proton is regarded as a soliton 'lump' of meson fields:

$$|p\rangle = V(t)U(\underline{x})V^{-1}(t) \quad (4)$$

with

$$U(\underline{x}) = \exp\left(\frac{2\pi i \underline{\tau} \cdot \underline{\pi}(\underline{x})}{f_\pi}\right), \quad (5)$$

where $\underline{\pi}(\underline{x})$ are SU(2) meson fields and the $\underline{\tau}$ are isospin matrices, and $V(t)$ is a time-dependent rotation matrix in both internal SU(3) space and external space. The Skyrme model embodies chiral symmetry, and is justified in QCD when the quarks are very light: $m_q \ll \Lambda_{QCD}$, which is certainly true for $q = u, d$, but more debatable for the strange quark. The Skyrme model should be good for long-distance (low-momentum-transfer) properties of nucleons, such as (the ratios of) magnetic moments $\mu_{n,p}$ [10], axial-current matrix elements $\langle p|A_\mu|p\rangle$ [11], etc.

According to the Skyrme model, the proton contains many relativistic current quarks, including $\bar{s}s$ pairs generated by the SU(3) rotations in (4). The nucleon angular momentum is generated in this picture by the slow rotation of the coherent meson cloud, so that if one decomposes the nucleon helicity in the infinite-momentum frame:

$$\frac{1}{2} = \frac{1}{2} \sum_q \Delta q + \Delta G + L_Z, \quad (6)$$

where the $\Delta q(\Delta G)$ are the net contributions of the quark (gluon) helicities, one predicts [11,12]

$$\sum_q \Delta q = \Delta G = 0, \quad L_Z = \frac{1}{2}. \quad (7)$$

In the meson picture, $L_Z = \frac{1}{2}$ arises from the mixing of isospin and conventional spin in the coherent cloud. In the quark picture, it should be interpreted statistically as an expectation value $\langle p|L_z|p\rangle = \frac{1}{2}$, much as inside the Deuteron $\langle D|L_z|D\rangle \simeq 0.06$ as a result of D -wave mixing. In this picture, the fact that $\Delta\Sigma = \frac{1}{2}\sum_q \Delta q = 0$ is a consequence of the topology of the internal SU(2) (or SU(3)) flavour group, and has nothing to do with the anomalous axial U(1) symmetry of QCD [13].

The Skyrme model is not necessarily in conflict with the idea of constituent quarks, and several models of chiral constituent quarks have been proposed [14], in which $|U\rangle = |u\rangle + u\bar{q}q\rangle + |uG\rangle + \dots$. However, as yet none of these has been derived rigorously from QCD.

As already recalled, the OZI rule [4] is to draw only connected quark line diagrams. This gains predictive power when it is further assumed that hadrons have only their naïve flavour compositions: $|p\rangle = |uud\rangle$, $|\phi\rangle = |\bar{s}s\rangle$, etc... However, it is known that OZI-forbidden processes such as $\phi \rightarrow 3\pi$, $f'_2(1520) \rightarrow 2\pi$, $J/\psi \rightarrow \text{hadrons}$ and $\psi' \rightarrow J/\psi + \pi\pi$ do occur at levels $\lesssim 10^{-2}$. In the cases of ϕ and f'_2 decay, these violations are conventionally ascribed to $|\bar{u}u + \bar{d}d\rangle$ admixtures in the meson wave functions, whereas in the cases of J/ψ and ψ' decay they are ascribed to pair-creation processes mediated by gluon exchanges. Are all OZI-forbidden processes restricted to the level $\lesssim 10^{-2}$, and can they all be explained by meson mixing or pair creation?

2. Prehistory

There has long been some evidence that there may be $\bar{s}s$ pairs in the nucleon. The first example may have been the $\pi - N$ σ term [15]:

$$\Sigma^{\pi N} \equiv \frac{1}{2}(m_u + m_d)\langle p|(\bar{u}u + \bar{d}d)|p\rangle, \quad (8)$$

which was first estimated using the Gell-Mann-Okubo mass formula and assuming $\langle p|\bar{s}s|p\rangle = 0$, to obtain

$$\Sigma_{\text{OZI}}^{\pi N} \simeq 25 \text{ MeV}. \quad (9)$$

However, the experimental value (hedged about with qualifications associated with the extrapolation from the Cheng-Dashen point, etc.), is estimated to be [15]

$$\Sigma_{\text{exp}}^{\pi N} \simeq 45 \text{ MeV}. \quad (10)$$

The discrepancy between (9) and (10) corresponds to

$$y_N \equiv \frac{2\langle p|\bar{s}s|p\rangle}{\langle p|(\bar{u}u + \bar{d}d)|p\rangle} \simeq 0.2, \quad (11)$$

with an uncertainty that may be ± 0.1 , whereas chiral symmetry and the successes of the pseudoscalar-meson mass formulae (2) suggest that $y_\pi \sim \text{few } \%$. For comparison with the experimental value (11), we recall that a Skyrme calculation [16] yields $y_N = 7/23$.

A second *a priori* example of OZI violation was the presence of $\bar{s}s$ pairs in the sea part of the proton wave function revealed by charm production in *deep-inelastic neutrino scattering* on an unpolarized target [17]. The reactions $(\bar{\nu}) + N \rightarrow \mu^\mp + \text{charm} + X$ receive

important contributions from $s \rightarrow c$ transitions $\propto \cos^2 \theta_c$, as well as from $d \rightarrow c$ transitions $\propto \sin^2 \theta_c$. Several experiments have found the need for an important $\bar{s}s$ contribution, and the recent NuTeV analysis [17] is stable when extended from LO to NLO QCD, yielding the following ratio of integrals of parton densities:

$$\kappa \equiv \frac{2 \int_0^1 dx (s + \bar{s})}{\int_0^1 dx (u + \bar{u} + d + \bar{d})} = 0.42 \pm 0.08 , \quad (12)$$

for $Q^2 \simeq 16 \text{ GeV}^2$ ¹. The x distributions of the s and \bar{s} parton distributions appear similar to each other, and comparable to those of the $\bar{u}u$ and $\bar{d}d$ sea components:

$$xs(x) \propto (1-x)^\beta : \beta = 8.5 \pm 0.7 , \quad (13)$$

and $-1.9 < \beta - \bar{\beta} < 1.0$ [17]. These can be regarded as measurements of an infinite tower of local twist-2 operator matrix elements: $\langle N | \bar{s} \gamma \partial^\mu s | N \rangle \neq 0$, which decrease relative to the corresponding $\langle N | \bar{q} \gamma \gamma^n q | N \rangle$ because of the harder x distribution of valence quarks.

The results (11,12,13) together imply that there are many non-zero matrix elements $\langle N | \bar{s}(\dots)s | N \rangle$, though they may depend on the space-time properties [18].

A first indication that the strange axial-current matrix element $\langle p | \bar{s} \gamma_\mu \gamma_5 s | p \rangle \equiv 2s_\mu \cdot \Delta s \neq 0$, where s_μ is the proton spin vector, came from measurements in *elastic $\bar{\nu} p$ scattering* of the $\langle p | \bar{s} \gamma_\mu \gamma_5 s | p \rangle$ matrix element [19], but this was not noticed until after the first EMC measurements [20] of *polarized deep-inelastic structure functions*.

3. The Strange Proton Spin

As is well known [21], polarized deep-inelastic electron or muon scattering is characterized by two spin-dependent structure functions $G_{1,2}(\nu, Q^2)$:

$$\frac{d^2 \sigma^{\uparrow\downarrow}}{dQ^2 d\nu} - \frac{d^2 \sigma^{\uparrow\uparrow}}{dQ^2 d\nu} = \frac{4\pi\alpha^2}{Q^2 E^2} \left[m_N (E + E' \cos \theta) G_1(\nu, Q^2) - Q^2 G_2(\nu, Q^2) \right] . \quad (14)$$

In the Bjorken scaling limit: $x \equiv Q^2/2m_N\nu$ fixed and $Q^2 \rightarrow \infty$, the naïve parton model predicts the scaling properties

$$m_N^2 \nu G_1(\nu, Q^2) \rightarrow g_1(x) , \quad m_N \nu^2 G_2(\nu, Q^2) \rightarrow g_2(x) , \quad (15)$$

where $g_1^p(x)$ has the following representation in terms of the different helicities and flavours of partons:

$$g_1^p(x) = \frac{1}{2} \sum_q e_q^2 [q_\uparrow(x) - q_\downarrow(x) + \bar{q}_\uparrow(x) - \bar{q}_\downarrow(x)] \equiv \frac{1}{2} \sum_q e_q^2 \Delta q(x) . \quad (16)$$

This expression can be compared with that for the unpolarized structure function $F_2(x) = 2xF_1(x)$:

$$F_2(x) = \sum_q e_q^2 x [q_\uparrow(x) + q_\downarrow(x) + \bar{q}_\uparrow(x) + \bar{q}_\downarrow(x)] . \quad (17)$$

¹The result shows no strong Q^2 dependence.

The quantity measured directly is the polarization asymmetry

$$A_1(x, Q^2) \equiv \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \xrightarrow{B_j} \frac{\sum_q e_q^2 [q_\uparrow(x) - q_\downarrow(x) + \bar{q}_\uparrow(x) - \bar{q}_\downarrow(x)]}{\sum_q e_q^2 [q_\uparrow(x) + q_\downarrow(x) + \bar{q}_\uparrow(x) + \bar{q}_\downarrow(x)]} , \quad (18)$$

or the related asymmetry $g_1(x, Q^2)/F_1(x, Q^2)$.

Much interest has focussed on the integrals

$$\Gamma_1^{p,n}(Q^2) \equiv \int_0^1 dx \, g_1^{p,u,d}(x, Q^2) , \quad (19)$$

which have the following flavour compositions in the naïve parton model:

$$\Gamma_1^b = \frac{1}{2} \left(\frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \frac{1}{9} \Delta s \right) , \quad \Gamma_1 = \frac{1}{2} \left(\frac{4}{9} \Delta d + \frac{1}{9} \Delta u + \frac{1}{9} \Delta s \right) , \quad (20)$$

where the net quark helicities Δq are related to axial-current matrix elements:

$$\langle p | \bar{q} \gamma_\mu \gamma_5 q | \rangle \equiv 2 s_\mu \cdot \Delta q , \quad (21)$$

where s_μ is the proton spin vector. Some combinations of the Δq are known from low-energy experiments. From neutron β decay and isospin SU(2), one has

$$\Delta u - \Delta d \equiv g_p = 1.2670 \quad (35) \quad (22)$$

and from a global fit to hyperon β decays and flavour SU(3), one has

$$\Delta u + \Delta d - 2\Delta s \equiv g_8 = 0.585 \quad (25) \quad (23)$$

Using (20) and (22), we recover the sacred Bjorken sum rule [22]

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6} g_A = \frac{1}{6} (\Delta u - \Delta d) \quad (24)$$

It is amusing to recall that Bjorken famously dismissed this sum rule as ‘worthless’ [22]! However, it led to the prediction of scaling and the formulation of the parton idea, and is now recognized (with its calculable perturbative corrections) as a crucial test of QCD, that the theory has passed with flying colours. Bjorken commented [22] that individual sum rules for the proton and neutron would depend on a model-dependent isotopic-scalar contribution, related in our notation to $g_0 \equiv \Delta \Sigma \equiv \Delta u + \Delta d + \Delta s$. The profane singlet sum rules [23] were derived assuming $\Delta s = 0$, motivated by the idea that, even if the OZI rule was not valid for parton distributions, surely the sea quarks would be unpolarized. As is well known, the data do not support these naïve singlet sum rules, which is surely more interesting than if they had turned out to be right.

The data on $\Gamma_1^{p,n}$ can be used to calculate Δs and $\Delta \Sigma = \Delta u + \Delta d + \Delta s$, with a key role being played by perturbative QCD corrections [24]:

$$\begin{aligned} & \left[1 - \frac{\alpha_s(Q^2)}{\pi} - 1.0959 \left(\frac{\alpha_s(Q^2)}{\pi} \right)^2 - 4 \left(\frac{\alpha_s(Q^2)}{\pi} \right)^3 + \dots \right] \Delta \Sigma(Q^2) \\ &= \Gamma_1^{p,n}(Q^2) - \left(\pm \frac{1}{12} g_A + \frac{1}{36} g_8 \right) \times \left[1 - \left(\frac{\alpha_s(Q^2)}{\pi} \right) - 3.8533 \left(\frac{\alpha_s(Q^2)}{\pi} \right)^2 \right. \\ &\quad \left. - 20.2153 \left(\frac{\alpha_s(Q^2)}{\pi} \right)^3 - 130 \left(\frac{\alpha_s(Q^2)}{\pi} \right)^4 - \dots \right] . \end{aligned} \quad (25)$$

The data on $\Gamma_1^{p,n}$ are highly consistent if these perturbative QCD corrections are included, yielding

$$\Delta n = 0.81 \pm 0.01 \pm ? , \quad \Delta d = -0.45 \pm 0.01 \pm ? , \quad \Delta s = -0.10 \pm 0.01 \pm ? , \quad \Delta \Sigma = 0.25 \pm 0.04 \pm ? \quad (26)$$

at $Q^2 = 5 \text{ GeV}^2$ [21]. The unspecified second error in (26) reflects possible additional sources of error that are difficult to quantify, including higher-twist corrections, the extrapolations of the measured structure functions to low x , etc ... However, there is clear *prima facie* evidence that $\Delta s \neq 0$.

The results (25, 26) can be compared with some theoretical calculations. For example, in the naïve Skyrme model with $m_{u,d,s} \rightarrow 0$, one finds [11]

$$\Delta u = \frac{4}{7}g_A , \quad \Delta d = -\frac{3}{7}g_A , \quad \Delta s = -\frac{1}{7}g_A , \quad \Delta \Sigma = 0 . \quad (27)$$

As commented earlier, in this model the smallness of $\Delta \Sigma$ is a consequence of the internal topology of the SU(3) flavour group. The absolute normalization of the Δq , namely g_A , is dependent on details of the model such as higher-order interactions, but the ratios (27) are quite model-independent. Substituting the experimental value $g_A = 1.26$ into (27), one finds

$$\Delta u = 0.71 , \quad \Delta d = -0.54 , \quad \Delta s = -0.18 , \quad (28)$$

which agree qualitatively with the experimental numbers (26). Improvement may be possible if non-zero quark masses (particularly m_s) are taken into account.

Several lattice calculations yield encouraging values of $\Delta \Sigma$:

$$\Delta \Sigma = 0.18 \pm 0.10 \text{ [25]}, \quad 0.25 \pm 0.12 \text{ [26]}, \quad 0.21 \pm 0.12 \text{ [27]}, \quad (29)$$

but, here again, there are problems with g_A and g_8 :

$$g_A = -.907(20) , \quad g_8 = 0.484(18) \text{ [27]}, \quad (30)$$

that may indicate the importance of a correct unquenching of quark loops. A recent development has been a calculation [28] of the total quark angular momentum:

$$J_q \equiv \frac{1}{2} \Delta \Sigma + L_q = 0.30(7) , \quad (31)$$

which indicates indirectly that the gluon contribution should be similar:

$$J_g = \Delta G + L_G \sim 0.2 . \quad (32)$$

One may hope in the future for considerable refinement of the present generation of lattice calculations: the challenge may then be to understand the physical mechanisms underlying the results found.

The perturbative evolution of polarized structure functions is well understood:

$$\begin{aligned} g_1(x, t) = & \frac{1}{2} \langle e^2 \rangle \int_x^1 \frac{dy}{y} \times \left[C_q^s \left(\frac{x}{y}, \alpha_s(t) \right) \Delta \Sigma(y, t) + 2N_f C_g \left(\frac{x}{y}, \alpha_s(t) \right) \Delta G(y, t) \right. \\ & \left. + C_q^{NS} \left(\frac{x}{y}, \alpha_s(t) \right) \Delta q^{NS}(y, t) \right] \end{aligned} \quad (33)$$

where $t \equiv \ln Q^2/\Lambda^2$, the coefficient functions C_q^s , etc., are all known to $\mathcal{O}(\alpha_s(t))$, and the scale-dependent parton distributions are controlled by evolution equations characterized by splitting functions P_{ij} that are also known to $\mathcal{O}(\alpha_s(t))$. Thus complete calculations to NLO are available [29]. The individual $\mathcal{O}(\alpha_s(t))$ correction terms are renormalization-scheme dependent, but the complete physical results are of course scheme-independent.

One of the issues arising at NLO is the possible impact of polarized glue [30]. It is known that $\Delta G \sim 1/\alpha_s$, which introduces an important ambiguity into the specification of the polarized quark distribution: since different possible definitions are related by

$$\Delta q_1(x, Q^2) = \Delta q_2(x, Q^2) + \mathcal{O}(\alpha_s) \Delta G(x, Q^2) \quad (34)$$

one finds an $\mathcal{O}(1)$ ambiguity $\delta(\Delta q) = \mathcal{O}(1)$. One possible prescription (\overline{MS}) is simply to define $\Delta q(x, Q^2)$ by the structure function $g_1(x, q^2)$. Another (AB) is to define the Δq so that a_0 (like a_3 and a_8) is independent of Q^2 , which implies that

$$\Delta q_{\overline{MS}} = \Delta q_{AB} - \frac{\alpha_s}{2\pi} \Delta G \quad (35)$$

To this order, one cannot distinguish between $\Delta G_{\overline{MS}}$ and ΔG_{AB} . All-orders fits to data should give the same result whatever prescription is used. However, at finite order they well differ, which provides one estimator for possible theoretical errors in the analysis. Typical AB fits yield [31]

$$\Delta G = 1.6 \pm 0.9, \quad (36)$$

providing an indication that $\Delta G > 0$, but no more. A corresponding AB fit [31] yields

$$a_0 = 0.10 \pm 0.05 \pm 0.07^{+0.17}_{-0.11}, \quad (37)$$

where the first error is experimental, the second is due to the low- x extrapolation, and the third is associated with the fit. If ΔG is as large as (36), it opens up the possibility that

$$\Delta s_{AB} = \Delta s_{\overline{MS}} + \frac{\alpha_s}{2\pi} \Delta G \simeq 0, \quad (38)$$

which might be thought to rescue the OZI rule [30]. It is therefore of great importance to try to measure ΔG directly.

A first attempt was made in a search for a production asymmetry in $\vec{p}\vec{p} \rightarrow \pi^0 + X$ [32]. There was no sign of a positive signal, but the theoretical interpretation is not very clean. A more recent attempt is via the large- p_T hadron-pair production asymmetry in photoproduction: $\vec{\gamma}\vec{p} \rightarrow (h^+h^-) + X$. A negative asymmetry: $A = -0.28 \pm 0.12 \pm 0.02$ is found [33], which has the opposite sign from that expected from $\gamma q \rightarrow Gq$, and is consistent in magnitude and sign with many polarized-gluon models. It therefore becomes important to confirm whether the effect is non-zero, and we also await eagerly data from COMPASS [34], from polarized beams at RHIC [35], and from polarized beams at HERA [36].

4. Hadronic Probes of Hidden Strangeness

According to the naïve OZI rule [4], if A , B and C are non-strange hadrons, then

$$Z_{ABC} \equiv \frac{\sqrt{2}\mathcal{M}(AB \rightarrow C + \bar{s}s)}{\mathcal{M}(AB \rightarrow C + \bar{u}u) + \mathcal{M}(AB \rightarrow C + \bar{d}d)} = 0 \quad (39)$$

In this case, the production of a predominantly $\bar{s}s$ meson such as ϕ or $f'_2(1520)$ would be due to a departure $\delta = \theta - \theta_i$ from ideal mixing [37–39], and, e.g.,

$$\frac{\mathcal{M}(AB \rightarrow C\phi)}{\mathcal{M}(AB \rightarrow C\omega)} = \frac{Z_{ABC} + \tan \delta}{1 - Z_{ABC} \tan \delta} \quad (40)$$

In the case of the ϕ and f'_2 , squared-mass formulae suggest

$$\tan^2 \delta_\phi \simeq 42 \times 10^{-3}, \quad \tan^2 \delta_{f'_2} \simeq 16 \times 10^{-3} \quad (41)$$

and in the latter case one may also estimate from the decay $f'_2 \rightarrow \pi\pi$ that $\tan^2 \delta_{f'_2} = (2.6 \pm 0.5) \times 10^{-3}$. There seem to be no particular problems for the OZI rule provided by ϕ production in πN collisions [39]:

$$R_{\pi N} \equiv \frac{\sigma(\pi N \rightarrow \phi X)}{\sigma(\pi N \rightarrow \omega X)} = (3.3 \pm 0.3) \times 10^{-3} \quad (42)$$

on average, making no phase-space corrections, whilst in NN collisions [39]:

$$R_{NN} \equiv \frac{\sigma(NN \rightarrow \phi X)}{\sigma(NN \rightarrow \omega X)} = (14.7 \pm 1.5) \times 10^{-3} \Rightarrow Z_{NN} = (8.2 \pm 0.7)\% \quad (43)$$

and in $\bar{p}p$ annihilation in flight:

$$R_{\bar{p}p} = (11.3 \pm 1.4) \times 10^{-3} \Rightarrow Z_{\bar{p}p} = (5.0 \pm 0.6)\% \quad (44)$$

which are not particularly dramatic.

In this context, some of the data from $\bar{p}p$ annihilation at rest at LEAR shown in Fig. 1 came as a great shock, especially [40]

$$R_\gamma \equiv \frac{\sigma(\bar{p}p \rightarrow \phi\gamma)}{\sigma(\bar{p}p \rightarrow \omega\gamma)} = (294 \pm 97) \times 10^{-3} \quad (45)$$

and [41]

$$R_{\pi^0} \equiv \frac{\sigma(\bar{p}p \rightarrow \phi\pi^0)}{\sigma(\bar{p}p \rightarrow \omega\pi^0)} = \begin{cases} (106 \pm 12) \times 10^{-3} & \text{in LH}_2 \\ (114 \pm 24) \times 10^{-3} & \text{in H gas} \end{cases} \quad (46)$$

The ϕ production rates exhibited no universal factor, as might be expected in a mixing model (or in a shake-out mechanism - see later), and were sometimes strongly dependent on the initial state [42]:

$$B(\bar{p}p \rightarrow \phi\pi^0) \Big|_{^3S_1} = (4.0 \pm 0.8) \times 10^{-4}, \quad B(\bar{p}p \rightarrow \phi\pi^0) \Big|_{^1P_1} < 0.3 \times 10^{-4} \quad (47)$$

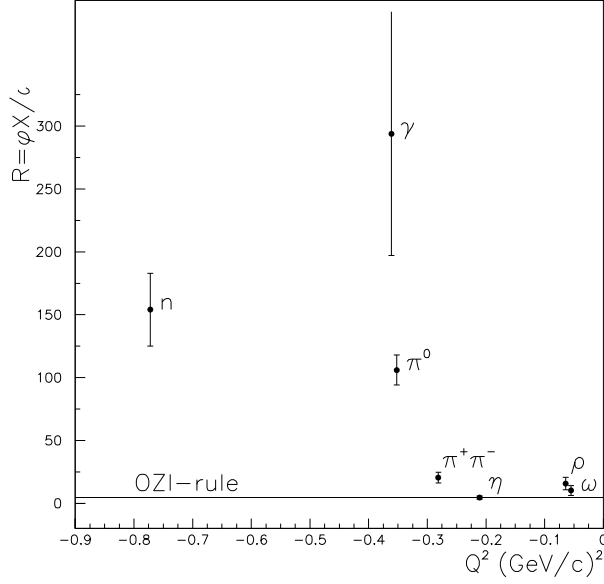


Figure 1. *Compilation of LEAR data testing the OZI rule in different $\bar{p}p$ annihilation channels.*

To add to the mystery, there were some $\bar{p}p$ annihilation channels where no large effect was observed [43,40]:

$$R_\eta = (4.6 \pm 1.3) \times 10^{-3}, \quad R_\omega = (19 \pm 7) \times 10^{-3}, \quad R_\rho = (6.3 \pm 1.6) \times 10^{-3} \quad (48)$$

The interpretation we propose [38,39] is that the proton wave function contains polarized $\bar{s}s$ pairs.

In general, if there is an $\bar{s}s$ component in the Fock-space decomposition of the proton wave function:

$$|p\rangle = x \sum_X |uudX\rangle + Z \sum_X |uud\bar{s}sX\rangle \quad (49)$$

where the remnant X may contain gluons and light $\bar{q}q$ pairs, the naïve OZI rule may be evaded by two new classes of connected quark-line diagrams, shake-out and rearrangement [38,39] as illustrated in Fig. 2. The former yields an amplitude

$$\mathcal{M}_{SO}(\bar{p}p \rightarrow \bar{s}s + X) \simeq 2\text{Re}(x^*z)P(\bar{s}s) \quad (50)$$

where $P(\bar{s}s)$ is a projection factor that depends primarily on the final state: $\bar{s}s = \phi, f'_2, \dots$. Rearrangement yields an amplitude

$$\mathcal{M}_R(\bar{p}p \rightarrow \bar{s}s + X) \simeq |Z|^2 T(\bar{s}s) \quad (51)$$

where $T(\bar{s}s)$ is a projection factor that may well depend on the initial state as well as the final state.

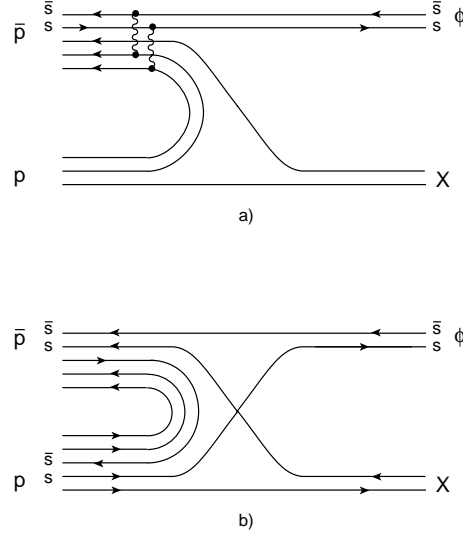


Fig. 1

Figure 2. *Shake-out and rearrangement quark-line diagrams that could contribute to ϕ or f' production in $\bar{p}p$ annihilation if the proton wave functions contains $\bar{s}s$ pairs [38,39].*

There are infinitely many possibilities for the quantum numbers of the $\bar{s}s$ pairs in (49). Assuming that

$$|p\rangle_{\frac{1}{2}} \ni |uud\rangle_{\frac{1}{2}} \otimes |\bar{s}s\rangle, \quad (52)$$

the simplest possibilities are those shown in Table 1. The first two of these are disfavoured by data on η production and by the non-universality of ϕ production. We favour [39] a 3P_0 state for the $\bar{s}s$, as in the vacuum (1). The triplet spin state should be antiparallel to the proton spin, as suggested by the polarized structure function data.

S	L	j	J^{PC}	State
0	0	1	0^{-+}	1S_0 ' η '
1	0	1	1^{--}	3S_1 ' ϕ '
1	1	0	0^{++}	3P_0
1	1	0	1^{++}	3P_1
0	1	0	1^{+-}	1P_1

Table 1

Possible quantum numbers of the $\bar{s}s$ cluster in the nucleon. We denote by \vec{S} and \vec{L} the total spin and orbital angular momentum of the $\bar{s}s$ pair, $\vec{J} \equiv \vec{L} + \vec{S}$, and the relative angular momentum between the $\bar{s}s$ and uud clusters is \vec{j} .

In such a picture, shake-out would yield predominantly K^+K^- and $K^0\bar{K}^0$ pairs in a relative S wave: we have argued [39] that this is consistent with LEAR data. This picture also predicts that the ϕ should be produced more strongly from 3S_1 $\bar{p}p$ initial states, whereas the f'_2 should be produced more from 3P_J initial states. The former is consistent with the previous data (46). What do more recent data indicate? The enhancement (46) of ϕ production from the 3S_1 initial state has now been confirmed with about 100 times more statistics [44]:

$$B(\bar{p}p \rightarrow \phi\pi^0)|_{^3S_1} = (7.57 \pm 0.62) \times 10^{-4}, \quad B(\bar{p}p \rightarrow \phi\pi^0)|_{^1P_1} < 0.5 \times 10^{-4}, \quad (53)$$

as seen in Fig. 3 whereas there is no similar trend for $B(\bar{p}p \rightarrow \omega\pi^0)$. It has also been observed that $\sigma(\bar{n}p \rightarrow \phi\pi^+)$ decreases as energy increases, similarly to the S -wave annihilation fraction, but there is no similar trend for $\sigma(\bar{n}p \rightarrow \omega\pi^+)$. The importance of ϕ production from the S wave is supported by the recent measurement of [45]

$$R_{pp} = \frac{\sigma(pp \rightarrow pp\phi)}{\sigma(pp \rightarrow pp\omega)} = (3.7 \pm 0.7^{+1.2}_{-0.9}) \times 10^{-3} \quad (54)$$

at an energy 83 MeV above the ϕ production threshold. The phase-space correction to (54) would be at least a factor of 10: in fact, there are indications that ω production may be from a mixture of S and P waves. There are also indications that f'_2 production may be enhanced in the P -wave initial state [44]:

$$R(f'_2\pi^0/f_2\pi^0)|_S = (47 \pm 14) \times 10^{-3}, \quad R(f'_2\pi^0/f_2\pi^0)|_P = (149 \pm 20) \times 10^{-3} \quad (55)$$

as also seen in Fig. 3. According to this picture, η production should also be enhanced in spin-singlet initial states, which is supported by the data [46]

$$R_\eta \equiv \frac{\sigma(np \rightarrow np\eta)}{\sigma(pp \rightarrow pp\eta)} = \frac{1}{4} (1 + |f_0/f_1|^2) \quad (56)$$

where f_i denotes the amplitude for the isospin = spin = i initial state at threshold. The measured value $R_3 \simeq 6.5$ suggests that $|f_0/f_1|^2 \simeq 25$.

An interesting recent development has been the observation of copious ϕ production in the Pontecorvo reaction [47], shown in Fig. 4:

$$R(\bar{p}d \rightarrow \phi n / \bar{p}d \rightarrow \omega n) = (154 \pm 29) \times 10^{-3} \quad (57)$$

which is expected to be dominated by S -wave annihilation. On the other hand, it has also been measured that [48]

$$R(\bar{p}d \rightarrow K\Sigma / \bar{p}d \rightarrow K\Lambda) = (0.92 \pm 0.15) \quad (58)$$

whereas a two-step model predicted a ratio of 0.012.

There have recently been many calculations of two-step contribution to $\bar{p}p \rightarrow \phi\pi$ in particular, including three- as well as two-particle intermediate states [49]. Individual intermediate states make calculable contributions to the imaginary part of the annihilation amplitude, but their relative signs are not known, and not always their spin decompositions, either. With suitable choices and estimates of the real parts, the data on

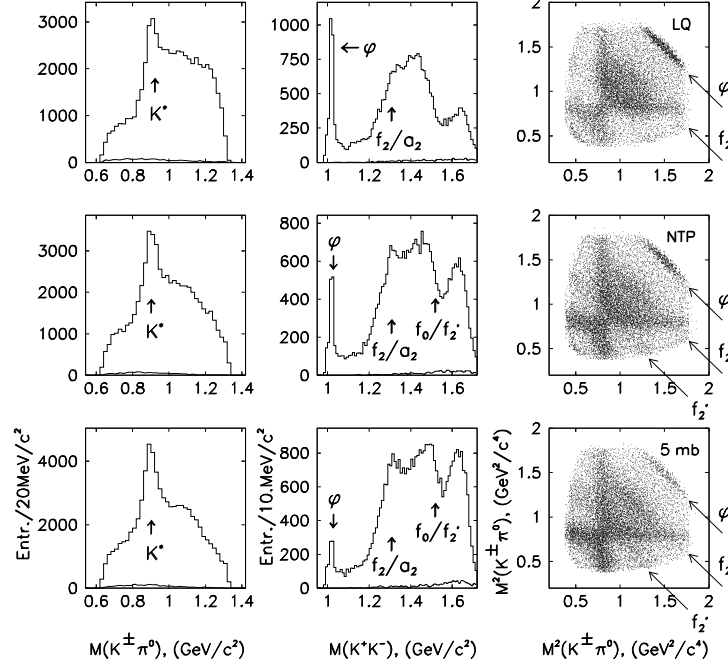


Figure 3. The $K^\pm\pi^0$, K^+K^- mass and Dalitz distributions in $\bar{p}p \rightarrow K^+K^-\pi^0$: the top (bottom) row of plots have more S -(P -)wave annihilations, and the ϕ (f') is more visible.

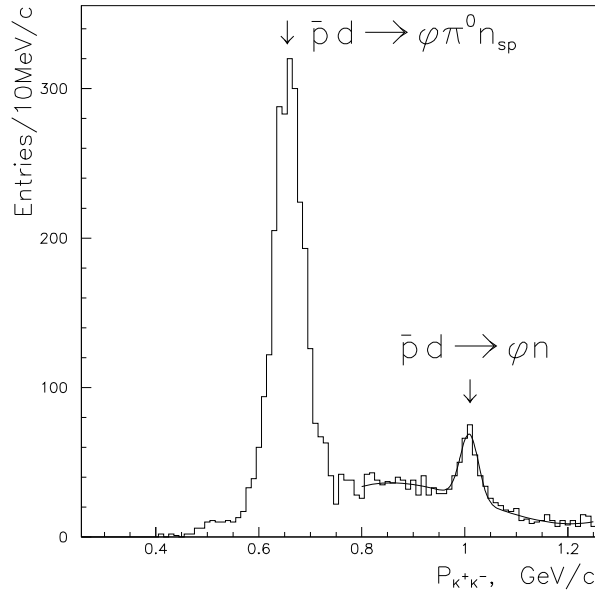


Figure 4. The momentum distribution of K^+K^- pairs in $\bar{p}D \rightarrow \phi + \dots$ shows clear peaks corresponding to $\bar{p}D \rightarrow \phi\pi^0 n$ and the Pontecorvo reaction $\bar{p}D \rightarrow \phi n$.

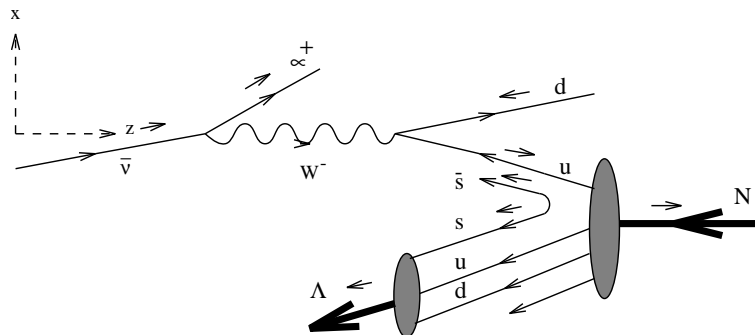


Figure 5. In deep-inelastic scattering with a polarized beam ($\bar{\nu}$ in the drawing), the polarized intermediate boson (W in the drawing) selects preferentially one particular polarization of struck quark (u in the drawing), which may in turn select preferentially one polarization of the spectator $\bar{s}s$ pair, which may be carried over to the spin of a Λ in the target fragmentation region.

$\sigma(\bar{p}p \rightarrow \phi\pi^0)|_{3S_1}$, can be fit. However, some challenges remain. Can the two-step prediction be made more definite? Can good predictions be made for other partial waves? Can the apparent anticorrelation with K^*K yields be understood? or the energy dependences of $\phi\pi$ and K^*K final states? Can the data on $f'_2\pi^0$ production and the Pontecorvo reaction be understood? Can the apparent OZI violation be correlated with other observables, as we discuss next?

5. Further Tests in Λ Production

The total cross section and angular distribution for $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ were measured in the PS 185 experiment at LEAR, and in particular the $\bar{\Lambda}\Lambda$ spin correlation was measured. It was found [50] that the spin-triplet state dominated over the spin-singlet state by about 2 orders of magnitude. This triplet dominance could be accommodated in meson-exchange models by suitable tuning of the K and K^* couplings. On the other hand, triplet dominance is a natural prediction of gluon-exchange models, and also of our 3P_0 $\bar{s}s$ model [51]. One way to discriminate between models is to use a polarized beam and measure the depolarization D_{nn} (i.e., the polarization transfer to the Λ) [51]. Polarized-gluon models would predict positive correlations between the p, g, s and Λ spins, so that $D_{nn} > 0$, whereas meson-exchange models predict $D_{nn} < 0$. The polarized-strangeness model predicts an anti-correlation of the p and s spins, and hence $D_{nn} < 0$. Data with a polarized p beam have been taken, and we await the analysis with interest. They may be able to distinguish between polarized-gluon and polarized-strangeness models. In the mean time, it is interesting that DISTO has recently measured [52] $D_{nn} < 0$ in the reaction $\bar{p}p \rightarrow \Lambda K^+p$, in agreement with the polarized-strangeness and meson-exchange models.

Another potential test is Λ polarization in deep-inelastic scattering [53], as illustrated in Fig. 5. Here the key idea is that when a polarized lepton ($\bar{\nu}, e, \mu$ or ν) scatters via a polarized boson (W^* or γ^*), it selected preferentially a particular polarization of the

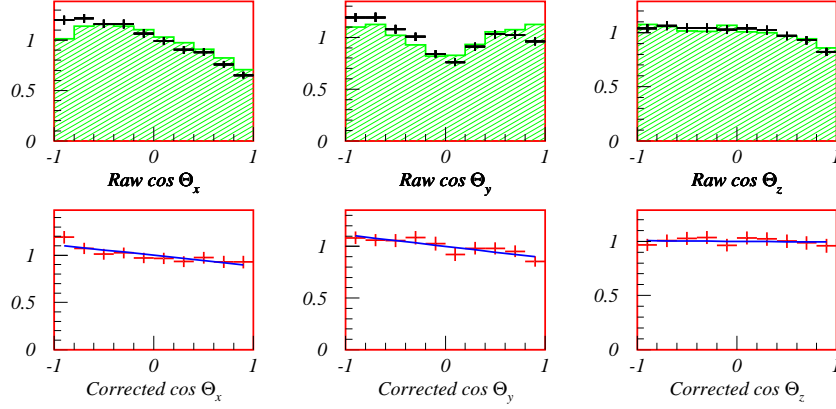


Figure 6. Data on deep-inelastic νN scattering [55] indicate negative Λ longitudinal polarization (left panel), as well as transverse polarization in the scattering plane (centre panel), but not outside it (right panel).

struck quark (u or d) in the nucleon target, even if the latter is unpolarized. The next suggestion is that the target ‘remembers’ the spin removed, e.g., $\bar{p} \rightarrow u^\uparrow + (u^\uparrow d^\downarrow (\bar{s}s)^\downarrow)$. The polarization of the $s(\bar{s})$ may then be retained by a $\Lambda(\bar{\Lambda})$ in the target fragmentation region. This prediction [53,54] was supported by early data on Λ polarization in deep-inelastic $\bar{\nu}N$ data. Recent NOMAD data [55] on deep-inelastic νN scattering confirm this prediction with greatly increased statistics, as seen in Fig. 6: the Λ polarization in the direction of the exchanged W is $-0.16 \pm 0.03 \pm 0.02$. The measurement of Λ polarization in the target fragmentation region is also in the physics programmes of HERMES in deep-inelastic eN scattering and of COMPASS in deep-inelastic μN scattering.

6. Strangeness Matters

The presence or absence of hidden strangeness in the proton is relevant to many other experiments in other areas of physics. Here I just mention just one example [56]: the search for cold dark matter [57]. The idea is that a massive non-relativistic neutral particle χ may strike a target nucleus depositing a detectable amount of recoil energy $\Delta E \sim m_\chi v_\chi^2/2 \sim \text{keV}$. The scattering cross section has in general both spin-dependent and spin-independent pieces. The former may be written as [58]

$$\sigma_{spin} = \frac{32}{\pi} G_F^2 \hat{m}_\chi^2 \Lambda^2 J(J+1) \quad (59)$$

where \hat{m}_χ is the reduced mass of the relic particle, J is the spin of the nucleus, and

$$\Lambda = \frac{1}{J} (a_p \langle S_p \rangle + a_n \langle S_n \rangle) \quad (60)$$

where

$$a_p = \sum_{q=u,d,s} \hat{\alpha}_q \Delta q \quad (61)$$

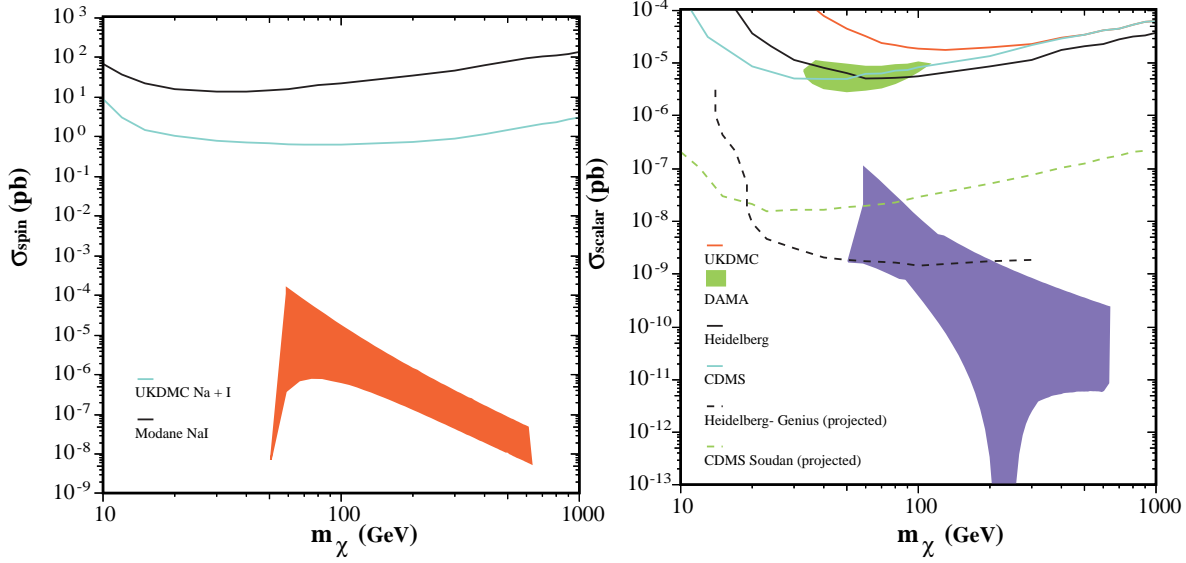


Figure 7. Estimates [58] (a) of the spin-dependent dark matter scattering rate in the minimal supersymmetric extension of the Standard Model, compared with experimental upper limits, and (b) of the corresponding spin-independent dark matter scattering rate, compared with upper limits and the measurement reported in [59].

(and similarly for a_n) with the coefficients $\hat{\alpha}_q$ depending on the details of the supersymmetric model, and the Δq being the familiar quark contributions to the proton spin measured by EMC et al. Likewise, the spin-independent part of the cross section can be written as

$$\sigma_{\text{scalar}} = \frac{4\hat{m}_\chi^2}{\pi} \left[Zf_p + (A - Z)f_n \right]^2 \quad (62)$$

where Z and A are the charge and atomic number of the nucleus, and

$$f_p = m_p \sum_{q=u,d,s} f_{T_q} \frac{\alpha_q}{m_q} + \frac{2}{27} f_{T_G} \sum_{q=c,b,t} \frac{\alpha_q}{m_q} \quad (63)$$

(and similarly for f_n) where the coefficients α_q again depend on the details of the supersymmetric model, and

$$m_p f_{T_q} \equiv \langle p | m_q \bar{q}q | p \rangle, \quad f_{T_G} = 1 - \sum_{q=u,d,s} f_{T_q} \quad (64)$$

We depend on measurements of the πN σ term for our knowledge of the f_{T_q} , and $\langle p | \bar{s}s | p \rangle$ plays a key role [58].

Fig. 7(a) compares a prediction for supersymmetric cold dark matter (in a favoured model) with experimental upper limits on the spin-dependent cross section, assuming that our galactic halo is dominated by supersymmetric relic particles [58]. A similar comparison for the spin-independent cross section is shown in Fig. 7(b). In this case, there is one experiment that reports possible evidence for a signal [59]. The uncertainties in the strangeness content of the proton are not sufficient to explain the discrepancy with our prediction. Perhaps our supersymmetric model is wrong? It would be good to see the reported detection confirmed, but this has not happened yet [60].

7. Issues for the Future

Many new experiments may cast light on the ‘strange’ nucleon wave function. These include πN scattering for the σ term, polarized eN structure functions and final-state asymmetries, ϕ and f' production in hadro-, photo- and electro-production [61], Λ polarization measurements in polarized eN , μN and νN scattering, charm production asymmetries in polarized μN scattering, further data on OZI ‘violations’ in $\bar{p}p$ annihilation, $\pi p/pp$ scattering, electro- and photoproduction. Low-energy experiments on parity violation in atomic physics [62] and eN scattering will also be useful.

Meanwhile, there are many theoretical challenges. Can the different models make quantitative predictions? Are different theoretical approaches really in conflict, or is there any sense in which they are different languages for describing the same thing? We need to understand better the dialectics between ΔS and ΔG , between constituent quarks and chiral symmetry, between intrinsic $\bar{s}s$ models [38,39] and the two-step approach [49]. Surely none of these religions has a monopoly of truth!

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